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An ethical analysis of hydrometeorological prediction and decision making: The case of the 1997 Red River flood

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Abstract

Weather, climate, and flood predictions are incorporated into human decisions in a wide variety of situations, including decisions related to hazardous hydrometeorological events. This article examines ethical aspects of such predictions and decisions, focusing on the case of the 1997 Red River flood in Grand Forks, North Dakota and East Grand Forks, Minnesota (US). The analysis employs a formal ethical framework and analytical method derived from medical and business ethics. The results of the analysis highlight issues related to forecast generation, communication of forecast meaning and uncertainty, responsibility for the use of forecasts in decision making, and trade-offs between the desire for forecast certainty and the risk of missed events. Implications of the analysis for the broader arenas of weather, climate, and flood prediction and disaster management are also discussed.

Keywords: Ethics; Floods; Red River of the North; Prediction; Weather; Climate

1. Introduction

Each day, weather, climate, and hydrological (hereafter *hydrometeorological*) predictions are generated by multiple public and private sector entities and disseminated to a wide range of audiences around the world. These predictions, which are based on a substantial scientific and technological infrastructure, are used by millions of individuals, government agencies, businesses, and other organizations to make decisions that affect human comfort, the environment, economies, and the safety of lives and property. Such predictions are unavoidably imperfect. Yet even when predictions are fairly accurate, forecast information that is incomplete, poorly disseminated, or ineffectively communicated can fail to generate benefits—or even cause harm. Hydrometeorological predictions can also become the source of difficulties if the information received is misinterpreted or misused. Examples range from minor inconveniences to natural disasters that cause deaths, billions of dollars in damage, and significant misery.

One example of such a disaster is the 1997 flood of the Red River of the North in the United States and Canada. The Red River Basin's geomorphology and climatology make it prone to flooding, and in 1997, a record-breaking flood was predicted several months prior to the event. Communities in the region prepared for weeks for a severe flood, constructing and raising dikes to prevent inundation. In Grand Forks, North Dakota, and East Grand Forks, Minnesota (US), new structural flood control measures had been introduced after the major flood of 1979, and with flood predictions from the US National Weather Service (NWS) and aid from the US Army Corps of Engineers (USACE), officials and citizens in the two communities worked to prepare for the flood and avoid major flood damage. At worst, most people expected water only in their basements or first floor. Yet NWS predictions of the flood were several feet too low, and the augmented dikes could not contain the water. Most of Grand Forks and East Grand Forks was flooded, some homes to their

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roofs. In these two communities alone (with a combined population of about 60,000), the flood caused more than $2 billion (1998 US dollars) in damage to property and infrastructure. Many residents and the communities as a whole were devastated. Some blamed the disaster on the NWS predictions.

Because of cases such as the 1997 Red River flood and other science policy developments, the weather, climate, and flood forecasting and research communities are recognizing the importance of understanding societal aspects of forecasts and incorporating this knowledge into forecast generation and communication (e.g., Pielke, 1999; Stern and Easterling, 1999; Sarewitz et al., 2000; Broad et al., 2002; National Research Council (NRC), 2006). An important component of societal aspects of forecasts is their inherent ethical dimensions. As discussed by Stern and Easterling (1999, p. 136):

> Ethical research questions address when and how to issue forecasts, how to deal appropriately with uncertainty, how forecast skill should be developed to achieve an appropriate distribution of the benefits, and how ethical beliefs … do and should affect the development, presentation, and dissemination of forecast information. Ethics thus provides a uniquely informative perspective from which to consider forecast generation, communication, and use in decision making.

Ethical considerations, particularly interpersonal and intergenerational equity, have been widely discussed in related scientific and technological contexts, such as natural disaster response and climate change (e.g., Howarth and Monahan, 1996; Glantz and Jamieson, 2000; Rothman, 2000). Ethical aspects of hydrometeorological *prediction*, however, have been less widely addressed. In this area, most ethics-related work has focused on seasonal-to-interannual climate forecasting. Issues that have been considered include the definition of societal benefit of climate forecasts, distribution of the costs and benefits of forecasts, inequities in forecast dissemination and access, and differential capacity to use forecasts in decisions (e.g., Pfaff et al., 1999; Broad et al., 2002; Lemos, 2003; Lemos and Dilling, 2007). While this work has articulated several important ethical considerations in seasonal climate forecasting, these have generally been discussed without reference to a formal, unified ethical framework. Lacking such a framework, it can be challenging to apply findings to other hydrometeorological prediction contexts. Moreover, many ethical aspects of hydrometeorological prediction remain unexplored.

In this article, we take a different approach, analyzing ethical aspects of hydrometeorological prediction and related decision making by employing a formal ethical framework derived from medical and business ethics (Beauchamp and Bowie, 2001; Beauchamp and Walters, 2003). To develop the analysis, we applied three general ethical principles—beneficence, justice, and autonomy—and the method of progressive specification (Beauchamp and Walters, 2003) to the case of the 1997 Red River flood. We focus on Grand Forks and East Grand Forks, where the flood damage and debate over the predictions were greatest, and where oral histories are available documenting details of the case.

As others have discussed, the Red River flood of 1997 raises issues for flood prediction, flood risk analysis, and risk communication, as well as flood-related decision making at the international, federal, state, local, and individual levels (e.g., Glassheim, 1997; NWS, 1998; Burn, 1999; Pielke, 1999; James and Korom, 2001a, b). The analysis presented here builds on this previous work, focusing on aspects of the case elucidated by applying a formal ethical framework and analytical method. This study also adds to the peer-reviewed literature on the 1997 Red River flood and flood hazards in general by incorporating individual decision makers' perspectives on the event and descriptions of their decisions, as compiled in oral histories.

Section 2 describes the three ethical principles and analytical method, and Section 3 reviews the case of the 1997 Red River flood. The method, progressive specification, involves successive iterations of examining the case and exploring the principles' meaning in the case context. Through this analysis, we elicited and elucidated key ethical issues related to prediction and decision making in the 1997 Red River flood, presented in Section 4. Because the three principles are interrelated, Section 4 also explores the interplay among them. Section 5 discusses broader implications of the analysis and applicability of the framework in other contexts.

The 1997 Red River flood is a complicated case. Decisions by multiple well-intentioned actors, past and present, interacted with a record-setting regional hydrometeorological event to create a local flood disaster. The purpose of the analysis is not to determine responsibility in this case, but rather to use the case as a template to identify and clarify general ethical issues in weather, climate, and flood prediction and related decision making. Given the many unexplored ethical issues in hydrometeorological prediction and decision making, the use of a formal ethical framework with a specific case provides a systematic focusing mechanism for the analysis. For many issues, the ethical analysis does not provide precise answers, but rather clarifies trade-offs and relative responsibilities inherent in prediction and decision making in potentially hazardous situations such as the 1997 Red River flood.

2. Ethical framework, principles, and analytical method

The ethical framework used here derives from work by Beauchamp and Bowie (2001) and Beauchamp and Walters (2003) to guide decision making in medical and business ethics. The framework developed by Beauchamp and co-authors (sometimes called the "Georgetown School" of applied ethics) is a composite drawn from several schools of thought in philosophical ethics. The primary source theories are: (1) consequentialism, including the various schools of ethical utilitarianism, and (2) deontological (sometimes known as Kantian) thought. In the first theory, ethical judgments are made based on the consequences of particular actions, while in the second, judgments are made based on guidelines for action that are defined a priori. Along with these primary source theories, the framework includes additions from the schools of ethical thought known as: "virtue ethics" (focusing on the need to consider character and moral motives along with judgments), the "ethics of care" (focusing on the idea that impartiality can be a hindrance rather than a help in some moral situations), and "casuistry" (focusing on the value of paradigm cases and analogical and practical judgments in ethical reasoning). Three principles form the poles of ethical consideration in this composite framework: *beneficence*, *autonomy*, and *justice*. These principles are described below, along with a particular method for incorporating them into a systematic ethical reasoning process, called *progressive specification* (Beauchamp and Walters, 2003).

2.1. Ethical principles

Here we provide a brief overview of the three ethical principles employed in the analysis. The principles are further elaborated for the case at hand and the context of hydrometeorological prediction in Section 4.

2.1.1. Beneficence

Beneficence considers the social and individual good or utility derived from an activity. More formally, beneficence (or lack thereof) is the societal "value added" (or lack thereof) provided by an activity, in other words, the activity's incremental value.

One way to understand beneficence is by considering the competitive market model of neoclassical economics. In this model, when markets are functioning properly (in particular, when costs are fully internalized to all producers) and no single actor wields influence over market outcomes, value added is closely related to what economists call normal profit (benefits minus costs, in the context of a normal rate of return on equity capital). This relationship provides part of the formal basis for using profit maximization as a criterion for achieving economic optimization. Through profit maximization, the entire (appropriately functioning) economic system directs each producer to maximize the social value of their economic activity. For products that, like many hydrometeorological predictions, are quasi-public goods (Freebairn and Zillman, 2002), achieving economic optimization becomes more complicated, but the overall social goal of maximizing the value added by an activity remains. In the context of hydrometeorological prediction, beneficence generally requires that forecast production and use generates net societal benefit—or, at a minimum, generates no net societal harm.

2.1.2. Autonomy

Autonomy seeks to ensure that individuals' pursuit of their own life-goals is fostered and not hindered, either by social activity or the activity of other individuals. Each individual must also give this same consideration to all members of society.

In medical ethics, autonomy requires that medical providers focus care and treatment on the needs of the patient and on maximizing a patient's opportunities for independent thought and action. Equally important, autonomy requires that patients have full knowledge about, and decision-making power over, their examination and treatment (to the extent possible given their health and mental condition and the state of medical knowledge). This includes knowledge of uncertainties in prognosis and treatment, as well as the likelihood of side effects. In the context of hydrometeorological prediction, autonomy suggests that, to the extent reasonable, forecasters and forecast communicators should provide potential users with the full information they have about the forecast in order to enable users to make their own independent decisions.

Autonomy also implies that individuals should actively seek and process information. In other words, autonomy requires that individuals attempt to locate and use reasonably available information in their decisions, rather than acting as passive recipients of information. Autonomy is thus not only a privilege that each member of society can expect; it is also a responsibility that each person actively empower his or her own free decision making.

2.1.3. Justice

Justice provides an overarching context to beneficence and autonomy by addressing inter-individual and intra-societal allocations. Justice contextualizes beneficence by balancing the benefit (or harm) that different individuals or groups accrue from an activity. It contextualizes autonomy by addressing the societal balance necessary in applying this individual-focused principle (a necessity implied in the statement that autonomy should be extended by each individual to all members of society).

Justice is often elaborated using the concept of "fairness," which considers how to appropriately apportion access, benefits, and costs. Fairness can be interpreted to mean equal apportioning, in which each individual is provided a per capita share of access, benefits, and costs, or it can be interpreted to mean a differential apportioning, based on individuals' different needs, capacity, and ability to bear costs. In this article we use a differential fairness consideration, derived in part from the "Difference Principle" of John Rawls (1999). This principle provides that social actions, policies, and rules must be considered in terms of their effects on the worst-off in society.[2]

[2]This consideration follows from Rawls' "Original Position," in which he considers the type of society its members would jointly want to develop if they all were behind a "veil of ignorance" concerning their individual

This Rawlsian scheme does not require eliminating all inequalities in the distribution of wealth, talents, access, and so on. Rather, it states that net worsening of the situation of the worst-off is not ethical, making this a minimum requirement of justice. A more proactive extension of this interpretation of justice can be derived from the principle known as the "Preferential Option for the Poor," described by the Roman Catholic Bishops of Latin America at their 1968 Conference in Medellin, Columbia (Consejo Episcopal Latinoamericano (CELAM), 2006). This more proactive principle insists not only on not harming the worst-off, but also on actively trying to improve their living situations and opportunities.

In the context of hydrometeorological prediction, justice considers the appropriate social sharing of and access to forecast information, along with appropriate sharing of the costs and benefits of forecast production and dissemination. In this article, justice is examined by combining the Rawlsian minimum requirement with the more proactive Medellin criterion.

2.2. *Method: progressive specification*

The method of *progressive specification* used in this study is derived from Beauchamp and Walters (2003), based in a rich repository of experience in medical ethics. In this method, one first performs an initial ethical examination of a situation (case) using the three principles (beneficence, autonomy, and justice). One then feeds the results back into further *reflection* on how the principles apply to the specific facts of the situation. The results of this reflection—a sharpened understanding of the relevant aspects of the three principles and of the situation—form the basis for a second round of examination. This may then lead to further rounds of reflection and re-examination. This iterative method has been found to provide improved *specification of judgment* for particular situations than that provided by a more traditional ethical method, in which specific rules are logically deduced from a set of basic principles and then applied in a "one-pass" manner to specific classes of cases.

In this way, progressive specification allows one to adaptively tune ethical perspectives to the complexity and particularity of situations. Underlying this approach is the concept that situations and ethical principles are intertwined, and that the principles are clarified and the situations can be more readily examined by employing a non-linear, dynamical method rather than a linear, static one. Through successive iterations, the dimensions and facts of the situation being examined help clarify the primary principles and deepen their application.

3. Case: 1997 flood of the Red River of the north

The case examined here is prediction and decision making leading up to the 1997 Red River flood in Grand Forks and East Grand Forks. Information about the case was obtained from NWS and USACE post-flood assessments (NWS, 1998; USACE, 1997; Bell and Halpert, 1998), peer-reviewed literature (e.g., Pielke, 1999; Burn, 1999; James and Korom, 2001a, b), oral histories (Glassheim, 1999; Glassheim et al., 2002), popular press coverage (e.g., Grand Forks Herald, 1997), and other relevant documents (e.g., Glassheim, 1997; Porter, 2001).

The Red River of the North flows northward along the Minnesota—North Dakota border in the US, into Manitoba, Canada. The Red River Basin is relatively flat, with low slopes that lead to slow runoff. As winter snow accumulations melt in the spring, the thaw tends to progress from south to north. This can create ice jams that further slow the river's northerly flow, generating backflow upstream and in tributaries. The region's geography and climate therefore make it prone to spring flooding (e.g., Porter, 2001).

During the fall and winter of 1996–1997, the Red River Basin experienced precipitation well above average, followed by an unfavorable sequence of warm and cold temperatures during the spring thaw. These two factors combined to produce record flooding in spring 1997 in much of the basin, starting south and moving north. After flooding began in the southern part of the basin, a blizzard and cold snap in early-mid April halted melting, froze standing and slowly moving water, and added snow. Several days later, a period of above average temperatures with no overnight freezing led to rapid melting, exacerbating the flood situation (Bell and Halpert, 1998; NWS, 1998). In Grand Forks and East Grand Forks, flooding was particularly severe: the river crested at a stage of 54.3 feet—more than 26 feet above flood stage, 4 feet above the highest measured flood in 1897[3], and more than 5 feet above the highest flood of the 20th century in 1979 (NWS, 1998; James and Korom, 2001a). Despite months of preparation by the communities and federal government agencies, the river inundated more than three-quarters of Grand Forks and nearly all of East Grand Forks, causing more than $2 billion (1998 dollars) in damage in the immediate vicinity (NWS, 1998; James and Korom, 2001b; Porter, 2001).

In preparing for the 1997 flood, Grand Forks and East Grand Forks relied on structural flood control measures built after the 1979 flood, as well as temporary measures based on flood "outlooks" and "forecasts" issued by the NWS North Central River Forecast Center (NCRFC) and

(*footnote continued*)
income, wealth, power, and abilities. In the Original Position, Rawls reasons that we would consistently want to consider the situation of the worst-off, since any one of us could *be* the worst-off. Each of us would then insist on an ethical criterion that decisions and actions not be allowed to hurt the worst-off in society, even if these actions would improve the per capita position of society. (The latter would be the criterion under strict utility maximization in consequentialist ethics.)

[3]Formal flood records at Grand Forks began in 1882, although higher floods were reported in the early-mid 19th century (Porter, 2001).

communicated through the NWS Weather Forecast Office (WFO) in Grand Forks. (Hereafter, NCRFC outlooks and forecasts are referred to collectively as "predictions," unless these terms are explicitly used to refer to specific NCFRC products.) Since its creation in 1979–1980, the NCRFC had issued river stage "outlooks" in March for two scenarios: average temperature and no subsequent precipitation, and average temperature and average precipitation. Given the severe flooding expected in 1997, the NCRFC issued outlooks earlier than usual, in February. The river stage outlooks for Grand Forks—East Grand Forks were 47.5 and 49.0 feet, respectively, for the two scenarios, and the NWS began warning of record flooding (NWS, 1998; Glassheim et al., 2002). In collaboration with the USACE, Grand Forks and East Grand Forks officials began working to protect their communities from the impending flood. The primary protection measure was adding sandbags and clay to the main river dikes, raising them to 52 feet (allowing several feet for possible prediction errors, waves, and other factors).

The first NCRFC "forecast" for Grand Forks—East Grand Forks was issued April 14 (more than a week after the blizzard) for a river stage of 50 feet. Over the next few days, as the river continued rising, the NCRFC gradually raised its forecasts. The communities and the USACE tried to elevate the main dikes further and then to build dikes in new locations to protect neighborhoods. However, the dikes were not high enough, and there was not enough time to implement alternate protective measures. On April 17, the river reached 51 feet, still rising, and dikes began to leak. By April 18, dikes began failing, and officials began evacuating neighborhoods as water flowed in. As the river continued to rise, local officials and the USACE realized they had no options left to protect the towns and evacuated most of the population. On April 21, the river crested at over 54 feet. Although a record flood had been predicted for months, many people moved little property, and some lost nearly everything (Grand Forks Herald, 1997; NWS, 1998; Glassheim, 1999; Pielke, 1999; Porter, 2001; Glassheim et al., 2002).

4. Ethical analysis

To present the results of the ethical analysis, we focus on four issues associated with prediction, communication, and decision making prior to the 1997 flood in Grand Forks—East Grand Forks, in Sections 4.1–4.4. Each subsection begins with an italicized summary of one of the four issues, followed by a more detailed discussion. Unless a specific reference is provided, interpretations of events are based on multiple accounts in NWS (1998), Pielke (1999), and the oral histories (Glassheim, 1999; Glassheim et al., 2002), along with the other references listed above.

4.1. Predictive information provided

Although the February 1997 outlooks of 47.5 and 49.0 feet provided by the NCRFC are best understood as low-flow and median predictions (NWS, 1998), the meaning of the predictions was not clearly communicated to local officials or residents. Some interpreted the higher outlook as a maximum (NWS, 1998; Pielke, 1999) and prepared accordingly. No "upper-bound" or "worst-case" scenario was provided, even though this was important information needed to prepare for the flood (James and Korom, 2001a).

The misunderstanding of the low-flow and median outlooks raises ethical concern from the perspective of autonomy, which requires providing the full information available about the predictions. NWS forecaster Wendy Pearson says she explained "the definitions of the outlook" at community meetings (Glassheim et al., 2002, p. 2), and information about the meaning of the predictions was available from the NCRFC. Yet the oral histories indicate that the meaning of the predictions was not clearly understood by Grand Forks officials, and this information did not accompany the predictions as they were more widely disseminated by the media, officials, and word-of-mouth. Without this information, decision makers did not fully understand how to interpret the NCFRC outlooks. More specifically, they did not understand that these predictions were conservative in terms of the potential severity of the flood.

If officials had understood the meaning of the outlooks, they might have decided to build temporary dikes higher or implement other flood protection measures. These actions not only would have provided additional protection; they may also have given officials and residents more time in later stages of the flood, as its severity grew apparent, to implement alternate plans. Further, this information might have encouraged officials and residents to develop better contingency plans, in case the flood was more severe. For officials, such plans might have included building backup dikes, considering flooding some areas to prevent the much broader inundation that occurred, or warning residents that they should prepare for possible flooding in their homes. For residents, such plans might have included purchasing flood insurance, moving important or valuable belongings out of their homes to safe areas, or packing up key belongings in case evacuation was required. Because these actions would likely have significantly reduced flood losses, clearly communicating the meaning of the predictions would have generated net societal benefit, i.e., enhanced beneficence.

Misunderstanding of the meaning of the predictions continued as the flood situation progressed. After the major blizzard in April 1997, snow surveys were unavailable for several days, delaying the issuance of the first NCRFC "forecast" (50 feet) until April 14. In the interim, the previous flood "outlook" of 49 feet was repeated, confusing some people who expected the extra snow to increase the predicted flood stage. From 14 to 18 April, the NWS slowly raised its forecasts, leading to further misunderstanding among decision makers (NWS, 1998; Porter, 2001; Glassheim et al., 2002). Thus, throughout the period leading up to the 1997 Red River flood, the oral histories indicate that lack of clear communication about how to interpret NWS flood predictions created misunderstanding and confusion among local officials and residents about the risk of extreme flooding and, in doing so, hindered effective decision making.

Because the communities were trying to protect against the river crest, a high-flow scenario (representing above-average precipitation and an unfavorable thaw cycle) would likely have been extremely valuable to officials and residents making flood preparation decisions. From a beneficence perspective, a high-flow scenario would almost certainly have provided significant net societal value, given the large amount of damage experienced. The minimum beneficence criterion of avoiding net social harm also appears to have not been met. From an autonomy perspective, providing a more complete set of forecast scenarios is an important part of providing full information (to the extent possible) in the face of flood risk. This suggests that low-flow and median event outlooks may not have been an appropriate set of standard NWS predictions in potential flood situations.

To generate forecast products for a wider range of scenarios and improve communication about the predictions' meaning, the NWS would likely require additional resources. Implementing such a plan involves justice considerations. If such changes were implemented across the US, general federal funding might be appropriate. Predictions provided for a local or regional area might most appropriately be funded through taxes of those at risk, e.g., through establishment of a flood-zone assessment area. If such a scheme were to be considered, further economic and ethical analyses of the relative burdens and gains experienced by different stakeholders would be needed to implement the scheme in a justice-sensitive way.

Note that providing a *definitive* high-flow or worst-case scenario is not practical, since a reasonable high-flow estimate invariably has some small chance of being exceeded. Even estimating a scenario with only, e.g., a 10% or 5% chance of exceedance would be challenging, given the complexity of the natural/human system involved in the flooding and the fact that the 1997 flood was an unprecedented event in the modern data record. Complicating matters, users do not agree on what type of improved flood prediction information they would like (NWS, 1998). Nevertheless, some type of high-flow scenario, with an explanation of its meaning, would have enhanced beneficence and autonomy in this case. In developing such information, forecasters would need to consider what information would be most understandable and most valuable to a range of decision makers. From a justice perspective, it is important to consider the needs of government officials, businesses, members of the public, and other stakeholders, paying special attention to the least well-off and those most vulnerable to negative impacts of flooding. Different types of information may be necessary to meet different users' needs, although from an autonomy perspective, all information should be made publicly available.

4.2. Predictive uncertainty

River predictions are inevitably uncertain. They are even more so when, as in case of the 1997 Red River flood, empirical knowledge is being used to predict an extreme event that has not previously been experienced. This uncertainty was not well communicated by NWS forecasters and was poorly understood by many residents and officials. It may also not have been fully understood by the forecasters themselves.

Officials did build dikes three feet higher than the February NCRFC outlook of 49 feet, to provide a margin of safety for possible prediction errors, waves, and dike stability. Yet, as discussed in Pielke (1999), the average error in the outlooks for Grand Forks from 1982 to 1997 was 3.5 feet, or 11.5% of the outlook value (equivalent to 5.6 feet for the 1997 outlook). Information concerning the expected uncertainty in the outlook based on predictive history was not communicated by the NWS, raising concern from the perspectives of autonomy and beneficence for the same reasons discussed in Section 4.1. The effects of this lack of communication of uncertainty were likely exacerbated by two factors. First, errors in NCRFC river stage outlooks for Grand Forks/East Grand Forks had been relatively small (less than 1.5 feet) over the preceding 2 years (NWS, 1998). In 1996, the NCRFC outlook had been quite accurate and had helped the communities prepare for a major flood that crested at 45.8 feet. Outlooks for 1993 and 1994 had somewhat larger errors, but were too high rather than too low. Thus, recent experience may have led local officials and residents to trust the predictions more than they would have if this experience had included significant errors on the low side.

Second, because the 1997 Red River predictions were for a record-breaking event, there were additional sources of uncertainty beyond the usual factors such as snowmelt, precipitation, water storage and flow, hydraulics, and ice jams. For example, because transbasin flows occurred in areas where they had not previously been observed, they had not been fully incorporated into predictions. Most importantly, NCRFC predictions translated estimates of flood discharge into river crest stages by relying on a rating curve that was derived empirically, in other words, based on observations of previous discharge-stage relationships (NWS, 1998). Because the discharge being predicted had not previously been observed in the instrumented record, it was beyond the boundaries of the rating curve. The NCRFC extended the curve using a logarithmic extrapolation that turned out, in retrospect, to underestimate the river stage by several feet (NWS, 1998). Local officials and residents appear to not have understood that the record-breaking nature of the prediction added significant predictive uncertainty. Instead, the fact that the prediction was only slightly higher than the flood of record made some community members confident that they could successfully fight the flood by augmenting the primary dikes (Glassheim, 1997, 1999; Porter, 2001).

NCRFC forecasters were aware of additional sources of uncertainty in the predictions, such as ponded water and potential transbasin flows, and they adjusted for these uncertainties as well as they could. However, this uncertainty appears not to have been clearly communicated to potential users of predictions. Moreover, it is not clear that, prior to the flood, the forecasters fully appreciated the historical uncertainty in the predictions, the additional sources of uncertainty in predictions of this flood, or their potential importance. With respect to the rating curve, in particular, it was known that the Red River can have a variable stage-discharge relationship at Grand Forks/East Grand Forks, with differences between the rising and falling phases of an extreme flood event (NWS, 1998). This hysteresis is caused in part by the geomorphology of the river, which has a nearly flat downstream slope that can generate significant backwater phenomena, restricting flow. In retrospect, this component of uncertainty should, by itself, have led forecasters to consider carefully how they extended the rating curve when discharge estimates went beyond the known stage-discharge relationship. The NWS (1998) post-flood service assessment recognized the importance of this phenomenon by recommending that the rating curve be updated and that future communications include predictions of discharge as well as stage.

Thus, both autonomy and beneficence would have been enhanced if NWS forecasters had fully recognized and accounted for the reasonably foreseeable sources of uncertainty in their predictions of a record-breaking flood, and if they had explicitly communicated with decision makers about the full scope of uncertainty. Moreover, different users have different capabilities and needs with respect to uncertainty information (NRC, 2006), indicating that justice will be an important consideration when deciding how to communicate uncertainty to different groups.

4.3. Responsibility for decision making

Responsibility for providing flood prediction information and for making flood-related decisions is divided between forecasters and users, and among federal, state, and local government agencies, businesses and other organizations, and individuals. Because of this distribution of responsibility, different actors in the Red River flood of 1997 appear not to have had a well-formed conception of their role in the prediction and decision-making process (Pielke, 1999). This unclear allocation of responsibility may have led individual actors not to fully accept their component of responsibility and to depend on others instead.

Official predictions for the 1997 Red River flood were provided by the NCRFC and the local NWS WFO, in conjunction with other federal agencies (such as the US Geological Survey) that provided data. Although flood predictions were available from other sources, such as a research group at the University of North Dakota and experienced local individuals, the NWS remained the official source of predictions for planning the flood fight. Relying on these predictions, Grand Forks city officials said, in retrospect, that they "didn't plan for failure" and "never thought about losing" (Glassheim et al. 2002, p. 16, p. 30; see also Porter, 2001, p. 53). Based on the outlook of 49 feet, with the help of the USACE, city officials built the dikes to 52 feet and believed that they would be able to protect the entire community. As this information was disseminated through the communities, most residents believed that their homes would be largely protected by the dikes, and so they did not evacuate significant property. Although the Federal Emergency Management Agency initiated an advertising campaign urging residents to purchase flood insurance, most did not, and some who asked insurance agents about flood insurance were told that they did not need to purchase it (Glassheim, 1999). Grand Forks officials did not begin considering evacuation until around April 10 and began warning of possible evacuations on April 16. Less than 2 days later, the city began ordering evacuations, and many residents were caught unprepared.

After the flood, some people in Grand Forks/East Grand Forks blamed local officials, while others blamed the NWS or other federal government agencies. Yet, the responsibility for losses in this case appears shared among forecasters and a range of decision makers. As discussed in Sections 4.1 and 4.2, NWS forecasters did not communicate the meaning of and uncertainty in the predictions as well as they could have. However, by relying so heavily on accuracy in the NWS predictions, local officials coordinating the flood fight appear to have given over some of their responsibility for decision making to the NWS, thus reducing their own autonomy. Many members of the hydrometeorological prediction community believe that most decision makers want a single forecast value (NRC, 2006), and some decision makers in the 1997 Red River flood said afterwards that they only wanted a single flood crest prediction (NWS, 1998). By providing a median flow prediction with no information about high-flow uncertainty, the NWS may have been responding to this pressure (real or perceived) and thus were attempting to meet forecast users' stated needs. Yet, as discussed by Pielke (1999), in doing so, forecasters took on a share of the responsibility for decision making, rather than concentrating on their area of expertise: prediction. This decision (whether made explicitly or implicitly) reduced decision-makers' autonomy as well as the beneficence of the prediction and preparedness efforts.

Responsibility is shared by other government agencies that contributed funding and other aid to the flood fight, such as the USACE (which has significantly more flood-fighting experience than local communities). Although the USACE initially recommended protective measures away from the main river channel, they did endorse local officials' flood-fighting plan, which did not consider the possibility of main dike failure (Porter, 2001). Residents also share responsibility for their losses. Although their fears were allayed by local officials' assurances that flood damage would be prevented, many residents seemed to believe, fundamentally, that the local and federal government could save them from an extreme flood. Under the circumstances, all actors appear to have acted in good faith and made the best decisions they could at the time. Yet collectively, this lack of clear allocation of responsibility among forecasters and different decision makers appears to have reduced overall beneficence. By not actively taking responsibility for information seeking and decision making, some actors also failed to exercise their responsibility with respect to the information-seeking component of autonomy.

As the flood evolved, most actors—including NWS forecasters, USACE engineers, local officials, and residents—became overwhelmed by the magnitude of the event and were not able to adjust rapidly enough. Perhaps this difficulty with anticipating and responding to extreme events is simply human nature. Yet, for communities at risk, providing complete protection from flooding is impossible. People's expectations that structural flood control measures and flood predictions will save them from all flooding are unrealistic. To the extent that residents and officials hold this belief, they are abdicating some of their responsibility in preparing for potential floods.

4.4. Concern about panic, false alarms, and complicated flood-fighting decisions

Grand Forks officials expressed concern about unnecessarily alarming residents and causing panic prior to the 1997 flood (Glassheim et al., 2002). Although this concern helped officials keep their communities relatively calm until the last minute, it appears to have to delayed communication with residents about the worst-case scenario and potential evacuations. This delay hindered residents' decisions to prepare for possible evacuation and take other protective action. Officials' concern also appears to have influenced them to postpone difficult decisions about how to prepare for a larger flood until it was too late.

Officials' desire to avoid alarming residents raises concern from the perspectives of both beneficence and autonomy. Although officials were attempting to enhance overall beneficence, they likely reduced it instead since, if residents had been warned earlier about the possibility of dike failure, they may have begun to move personal property out of the flood risk area earlier and more successfully. To the extent that concern about panic did delay communication of potentially useful information, it also reduced residents' autonomy. This situation suggests a possible trade-off between beneficence (promoting overall societal good by avoiding panic) and autonomy (providing all available information) in warning about potential disasters. Yet, many disaster experts believe that the potential for panic and civil unrest in response to disaster warnings is a myth (e.g., Clarke, 2002; Fischer, 2006), so this trade-off may not, in fact, be real.

Grand Forks officials' concern about panic also highlights citizens' responsibility to appropriately process information about potential disasters when officials recognize and respect their autonomy by providing such information. If citizens are too sensitive to "false alarms" or "near misses," forecasters and officials may feel they need to be certain before notifying citizens of potential disasters and taking protective action. Achieving certainty with sufficient time to take effective action may not be possible. Moreover, focusing on certainty (minimizing false positives) generally increases the chances of missed events (false negatives; e.g., Green and Swets, 1988), and doing so can fail to adequately account for the potential catastrophic consequences of a false negative—as occurred in the Red River flood of 1997. In extreme events, preparing for the unlikely, but possible, worst-case scenario can potentially make the difference between a near-disaster and an actual disaster. Citizen attitudes that encourage forecasters and officials to minimize false alarms therefore raise important concerns for disaster management from autonomy and beneficence perspectives.

It is not clear whether the entire communities of Grand Forks/East Grand Forks could have been protected from the flood, even if the forecasters had warned of a 54 foot or higher crest (Pielke, 1999; Glassheim et al., 2002). Had the floodwaters been contained between the dikes, the river would have crested even higher than 54 feet, and building structurally sound temporary dikes even two feet higher than those that were built would have been challenging, if not impossible. Such a prediction—or even a recognition that such an event was possible—would likely have forced local officials and the USACE to plan for possibly allowing some homes to flood in order to save the remainder of the communities. Grand Forks city engineer Ken Vein addressed his concern about such a plan after the flood:

> Had we tried to plan for a larger flood, we would have been in the position of having to determine fall-back lines. If we had tried to implement a secondary line of defense the entire length of the city I think it would have been utter chaos out there. The people on Belmont Road who would have been on the river side of the secondary line of defense would have said that we were giving them up when there wasn't even water in their backyards.... In order to react quickly enough, we would have had to have started well in advance, and I agree with Jim Campbell [Manager, Emergency Operations Center] that we would have had civil unrest had we tried to do that. (Glassheim et al. 2002, p. 30).

Making the choice to risk sacrificing some homes near the river to save those further away—or even allocating some flood-fighting resources to prepare for such a possibility—would have been controversial and viewed by some as "unfair," i.e., unjust, and local officials were concerned about considering such controversial decisions before the flood grew severe. However, making such a decision would likely have generated large net societal benefit, both by reducing damage to many homes and by preventing the widespread destruction that threatened the communities' economies and social fabric—concerns that also have strong justice implications. In the 1997 Red River flood, the homes that would have been sacrificed for secondary containment were, in fact, completely destroyed, so justice concerns related to positioning fallback lines turned out not to be relevant. This is only apparent in retrospect, however, indicating that the interplay between beneficence and justice can be significant (and complex) when making flood-fighting decisions.

5. Discussion

The results of our analysis point to significant missed opportunities for increasing beneficence, autonomy, and justice in the generation, communication, and use of predictions prior to the 1997 Red River flood in Grand Forks and East Grand Forks. From a beneficence perspective, the preparation of a meaningful high-flow scenario, along with improved communication about the meaning of the predictions and their uncertainty, had strong potential to help reduce property losses more than these measures would have cost—if such information had then been used in preparing for the flood. Effectively communicated information about a high-flow scenario and predictive uncertainty would have improved decision makers' understanding of the potential severity of the flood. With such knowledge, local and USACE officials could have created better contingency plans for fighting the flood, and they could have advised citizens to relocate movable property out of the likely flood zone in the weeks prior to the event. Citizens and businesses, in turn, would have better understood the risk of severe flooding to their property, aiding their decisions about purchasing flood insurance, moving property, and planning for a potential evacuation (Glassheim, 1999).

By providing officials and residents with more complete information for potential use in decision making, a high-flow scenario and improved uncertainty communication would also have enhanced autonomy. For forecasters, autonomy requires only that this potential be addressed. Decision makers have a symmetric autonomy responsibility to seek such information and use it appropriately. This includes a responsibility to avoid lowering their responsiveness to potential threats because they are sensitive to the possibility of false alarms.

The lack of a high-flow scenario and lack of effective communication about the predictions' meaning also raises justice considerations. The low-flow prediction that accompanied the median prediction was generated primarily to serve river navigation needs. The set of low-flow and median scenarios provided by the NCRFC does not adequately address the needs that communities at risk from extreme flooding have for a high-flow scenario. Because the predictions' meaning was not clearly communicated, different decision makers interpreted the predictions differently, leading to another set of potential justice concerns. In addition, if a high-flow scenario had been prepared, or if the meaning of the predictions and their sources of uncertainty had been communicated more clearly, the empirical limitation of the Red River rating curve at Grand Forks/East Grand Forks may have been more apparent prior to the flood. This last consideration illustrates how attending to ethical criteria can focus attention on highly technical, yet critical, aspects of flood prediction.

These results from our ethical analysis of the 1997 Red River flood provide broader lessons for hydrometeorological prediction, especially in potentially hazardous situations. When an extreme weather, climate, or flood event is possible, our analysis suggests that, at minimum, high, expected (median), and low scenarios should be prepared and disseminated. Such a set of predictions can help decision makers both prepare for a possible worst-case scenario and avoid misinterpreting asymmetric predictive information. For predictions of both potentially extreme and other types of events, forecasters should clearly communicate information about the predictions' meaning, uncertainties in the predictions (including likelihood of different outcomes), and the limits of knowledge that constrain the predictions' accuracy. Our analysis also suggests that forecasters and forecast disseminators (e.g., the media) have a responsibility to provide relevant public education and to work with decision makers to help them understand predictive information and exercise their own responsibility by applying it.

The analysis indicates that in the 1997 Red River flood, officials may have been overly concerned about false alarms, and forecasters, officials, and residents may have underestimated the potential for—and potential costs of—an underforecast event. These issues are linked to a larger set of philosophical concerns about the appropriate balance between the risk of false positives (false alarms) and that of false negatives (missed events). One example is deterrence policy related to the possibility of large-scale nuclear war. Since early in the Cold War period, American and Soviet/Russian nuclear deterrence policy has been strongly influenced by concern about avoiding the consequences of a false negative judgment concerning the risk posed by the other party (K. Schrader-Frechette, public address, Humphrey Center, University of Minnesota-Minneapolis, April 2000).[4]

[4]Of course, the "mutually assured destruction" posture resulting from the American-Soviet/Russian deterrence standoff highlights the simultaneous need to strongly avoid false positive judgments of hostile action by the other party.

In contrast, in many other arenas of societal decision making, avoidance of false positive judgments has been preeminent. For example, the public debate in the United States on modern global climate change (separate from the now-established scientific consensus on this topic; Intergovernmental Panel on Climate Change (IPCC), 2007) has tended to emphasize the need for clear demonstration that anthropogenic greenhouse gasses are causing global warming before taking significant mitigating action—indicating a primary focus on avoidance of a false positive. Because action to mitigate greenhouse emissions will require significant redirection of economic resources (Pacala and Socolow, 2004), the potential for false positives should be taken seriously. However, not acting to mitigate greenhouse emissions has potential to generate even larger economic and social costs (IPCC, 2007; Rowley et al., 2007), illustrating the importance of avoiding a serious false negative error. A similar emphasis on avoidance of false positives occurred in early attempts to mitigate chlorinated fluorocarbons (CFCs) to curb anthropogenic destruction of stratospheric ozone. As international negotiation over CFCs continued, however, the emphasis shifted to recognition that a false negative would involve great loss (massive reduction of stratospheric ozone) and that waiting until there was scientific certainty to begin CFC mitigation would make effective action impossible. Thus the Montreal Protocol stipulating strong mitigation measures was enacted *before* there was scientific certainty that CFCs did, in fact, lead to ozone destruction (Benedick, 1991). For mitigation of very long-lasting environmental effects (e.g., millennia of sea level rise, acidification of the world ocean) from anthropogenic climate change, a parallel case to that of stratospheric ozone has been/is now being made: in other words, the potential for loss created by a false negative judgment is huge, and waiting until a false positive can be absolutely ruled out (e.g., IPCC, 2007) could mean waiting until effective mitigating action would be extremely difficult if not impossible (Pacala and Socolow, 2004; Socolow and Pacala, 2006). Moreover, a false negative error is likely to significantly harm the worst-off, a significant justice consideration (Rowley et al., 2007).

The tendency to over-attend to the risks and costs of false positive judgments and to under-attend to the risks and costs of false negative judgments in many arenas is a general concern about the use of scientific information in public policy making (Schrader-Frechette, 1991, 1996; D. Jamieson, personal communication, 2003). It is also connected to broader issues in disaster management. For example, it was well-known prior to Hurricane Katrina in 2005 that such a storm would pose significant risk for severe flooding in New Orleans (e.g., Laska, 2004; Bourne, 2004). Yet government decision makers were wary of warning and evacuating people unnecessarily, and they waited to implement evacuation and other disaster management plans (including evacuation aid for people without transportation and other vulnerable populations) until, for some people, it was too late. The consequences were tragic, especially for society's most vulnerable populations. Such issues are growing more important as, in the United States and around the world, population and property at risk from floods, hurricanes, and other disasters increases (e.g., Pielke and Downton, 2000; International Strategy for Disaster Reduction (ISDR), 2004). In many flood risk zones, residents rely heavily on structural measures such as dams, detention ponds, culverts, dikes, and levees, and on other forms of modern technology to protect them from floods and other disasters. But structural measures have limitations, and they are only designed to protect against floods up to a certain level (e.g., Tobin, 1995)—making prediction and effective warning communication most important for extreme events, when both the risk and uncertainty are greatest. Our analysis of the 1997 Red River flood suggests that the formal ethical framework developed here could also be used retrospectively to elucidate important issues related to prediction, communication, and decisions in the Katrina flood and other disasters. More generally, such ethical analyses can aid policy planning by illuminating, in a prospective way, key aspects of the interplay among science, technology, decision making, and societal outcomes in hydrometeorological forecasting, natural disaster management, and other areas.

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